INDOOR LOW SPEED AIR JET FLOW: 3-DIMENSIONAL PARTICLE STREAK VELOCIMETRY

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ABSTRACT

This paper presents results from a larger project on the use of Particle Streak Velocimetry (PSV) to determine the air movements in ventilated rooms. With this method it is possible to record the instantaneous three-dimensional velocities over a large area. The method has been optimised for large field of views $\approx 10 m^2$ which is required for ventilation applications. With the use of small light particles suspended in the air, we can present images of their tracks. Then, with the help of computerised image processing and with Stereo-Photogrammetry analysis, we can obtain the three-dimensional velocity.
This particular application deals with the evaluation of the instantaneous velocities of a low speed jet. The isothermal jet flow was issued from a small nozzle (diameter d=5.0 cm), in a room of the size 3.6x3.6x2.5 m (LxWxH). The test was conducted for the supply velocity of 30 cm/s, corresponding to Reynolds number, $Re_d = 1075$.
This paper treats the results obtained with the PSV method and presents an analysis of the instantaneous three-dimensional velocities in the jet flow. Smoke has also been used to visualise the jet flow.
The results show that our whole-field method can be a good tool for measuring three-dimensional velocities in rooms and to visualise the indoor-climate. The method should be improved by finding homogeneous and light particles. It is also important to increase the resolution of the photographs.

KEYWORDS

Air velocity, Full Scale Experiments, Particle streak velocimetry, Measuring techniques, Jets.

INTRODUCTION

Air movements in rooms are generated by a number of factors; jets from ventilation systems, plumes from warm surfaces or down-draught from cold windows or walls.
A room covers a large area and generally the air movements are three dimensional. Therefore, measurements of these flow fields with single point techniques require an enormous effort and often the result will be poor.

A method which could instantaneously register information from a large area, a so called whole-field-method, would therefore be of great practical value.

"Particle Velocimetry" (PV) is a generic term for a group of whole-filed methods that are used for recording velocities in fluids. In most cases where these methods are used, the field covered is relatively small.

"Particle Streak Velocimetry" (PSV) has been selected by us as the method for registering three-dimensional air movements in a whole room. The method is based on measurements made on individual particles. The particles are lighted by a light-sheet and photographed. On the photograph the particle-movements are registered as streaks.

By use of Stereo-Photogrammetry it is possible to measure the movements in all three directions. This method is relatively new in ventilation studies, some early results were presented by Kaga, A., Inoue, Y. and Yoshikawa, A. (1990) and later by Scholzen, F. and Moser, A. (1996). An example of a recent use of stereoscopic viewing for measuring velocities is found in Grand et al (1995). There are a lot of questions, about the accuracy and the limitations, yet to be answered. For example; Do the particles follow the air movements? How high resolution on the photos do we need to get good results? Is the Image-Processing-Program able to find the right co-ordinates?

In this paper we use this method for making measurements of the three-dimensional velocities of a jet flow. For the same conditions, measurements with film probe has been carried out, see Todde et al (1998).

Our aim with this project was to answer some of the questions and also to identify details that has to be improved.

Principle of stereo-photogrammetry

The principle of stereo photogrammetry is well known, see Fig. 1. A point in the room with co-ordinates (X,Y,Z) is projected onto the image plane of two cameras (camera one and two). The projections have co-ordinates (x_1,y_1) and (x_2,y_2) respectively on the image planes. Because the point in the room is viewed from slightly different angels there is a difference in position. The difference in position, on the two images, is the parallax $p=(x_1-x_2,\ y_1-y_2)$.

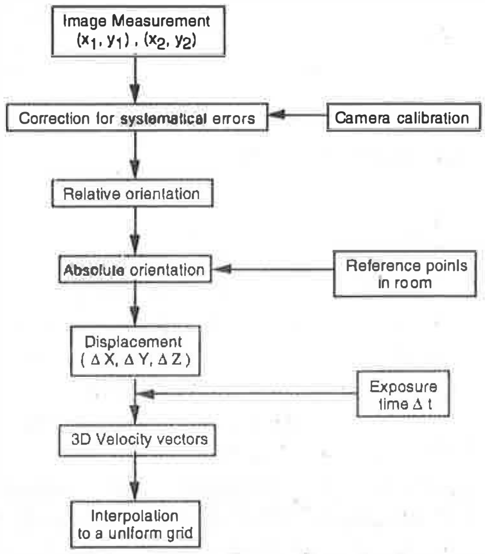

Fig. 1: Steps in stereo-photogrammetry

The main geometrical factors are:

Scale factor S: $S = \dfrac{Z}{f}$

Distance to object/base $= \dfrac{Z}{b}$

Where Z is the distance between the camera and the light sheet and f is the focal length of the camera and b is the distance (base) between the cameras.

In the tests we had b =0.3 m , Z= 2.15 m and f = 51.9 mm. This gives S= 41.4 and Z/b = 7.16.
The parallax p is inversely proportional to the distance of the object.

$$p = \frac{b}{S}$$

In our case the parallax is equal to 7 mm. The resolution in the out of plane component is much less than the resolution of the in plane co-ordinates. As model equations, for relating the recorded image co-ordinates to the co-ordinates in the room, the coplanarity equations have been used. For more details and presentation of simulations of the accuracy, see Piechocinski et al (1997).

EXPERIMENTAL METHOD

The climate chamber

The experiment took place in a climate chamber (see Fig. 2 and 3), LxWxH = 3.6x3.6x2.5 m, specially designed for visualisation. The ceiling and one of the walls are made of glass.

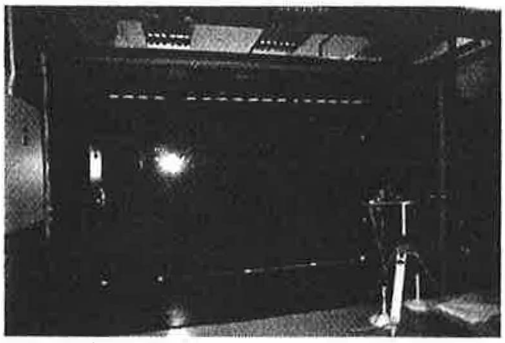
Fig. 2: Climate chamber for visualisation

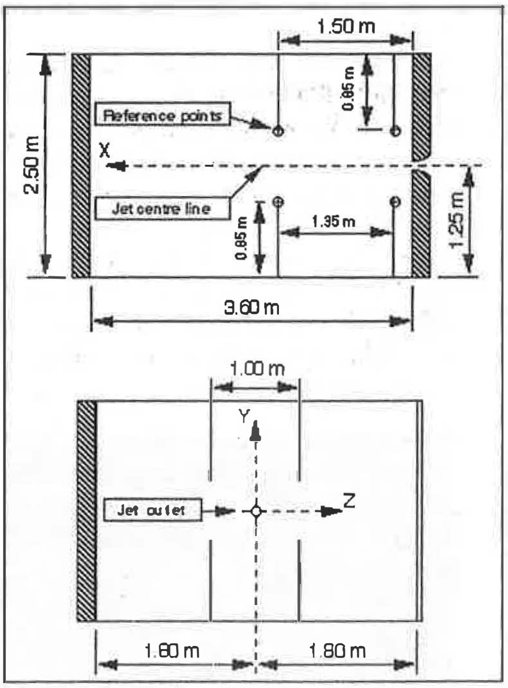

Fig. 3: Dimensions of climate chamber

The jet flow

The isothermal jet flow was issued from a small nozzle (diameter d=5.0 cm) located on the centre of one of the side-walls. Eight thermocouples in the room and two in the nozzle, before the honey-comb, were installed. The test was conducted for the supply velocity of 30 cm/s.
The nozzle design with it's main components is illustrated in Fig. 4.

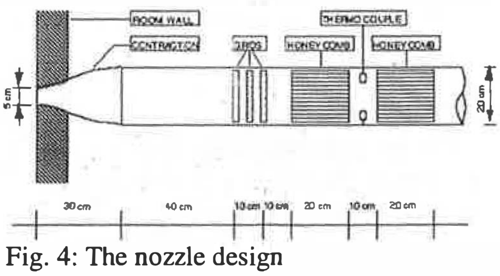

Fig. 4: The nozzle design

Particles
In the whole-field method particles, that follow the air motions, are photographed.
Particles, with a typical diameter of 80 µm, are introduced into the nozzle just before the opening in the wall. This is made with a purpose made injector (see Fig. 5) that spreads the particles through three holes in the top of the nozzle. To be able to inject the particles, despite the over-pressure within the nozzle, some air-pressure was introduced to the top of the injector.

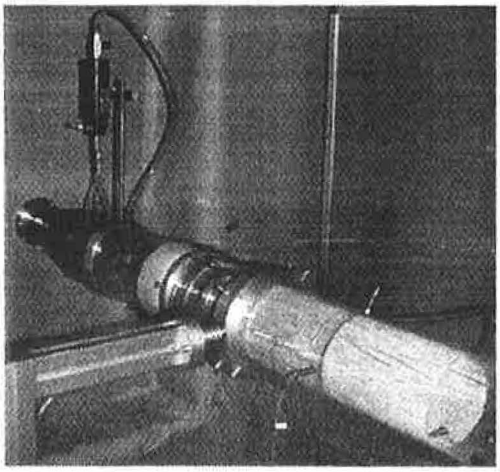
Fig. 5: Nozzle with particle injector

To observe the particle movements in a region along the centreline of the jet a light sheet is used. This light-sheet is produced by 18 halogenlamps with a total power of 5.4 kW. The thickness of the light-sheet is about 8 cm.

Photographing
The jet is photographed with two measuring cameras (Rolleiflex) on 6x6 cm black and white film. The cameras (see Fig. 6) are provided with reseau marks (reference crosses) engraved into the camera body. These reference points makes it possible to correct for systematic errors as film shrinkage and lens distortions.

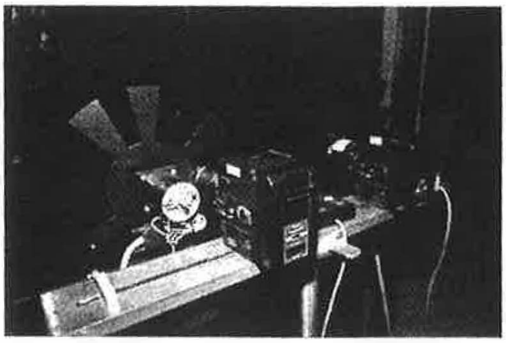
Fig. 6: Cameras and choppers

Within the flow-field there is a system of eight reference points (Fig. 7) whose co-ordinates are known with a high accuracy. This co-ordinate system makes it possible to convert the image co-ordinates to co-ordinates in the room (absolute orientation).

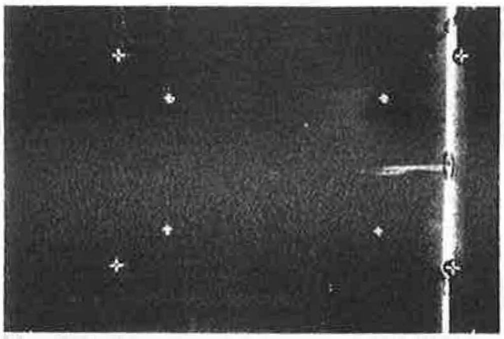
Fig. 7: Reference-points and particles in the room

Each particle gives rise to a streak (see Fig. 7) on the photographs. The length of these streaks depends on the time the camera has been open and the particle velocity.
If the particles, during the exposure, enter or leave the light-sheet the length of the streaks are not proportional to the velocity. To be able to decide whether or not a particle has stayed within the light sheet, a chopper (see Fig. 6), with a known speed of rotation, has been put in front of the camera. This shopper cuts the streak into three substreaks of different lengths, see Fig. 8.

Fig. 8: A streak made by a particle

For each streak the ratio between the lengths of the substreaks has to be correct. The fact that the streak is divided into substreaks of different lengths makes it also possible to identify the direction of movement. Use of coloured streaks for identifying the direction of the flow has also been explored, Linden, E. and Sandberg, M. (1997).

Computerised Image-Processing

After the film has been developed the photos are stored on a photo-CD with the highest standard resolution level which is 3072*2048 pixels. On the negative the side length of one pixel is 0.03 mm, which corresponds to 1.2 mm in the room.

The Image-Processing-Program make a binary-photo (only black and white) from the original photo. Selection of a threshold sets the background to white and the pixels belonging to the streaks become black. This makes it in principle possible for the computer to find the streaks. The streaks with the right proportions, between the different parts, are chosen and the co-ordinates of the start- and endpoints are measured. By using the measured photo-co-ordinates for the reference-points in the room and the streaks it is possible to calculate the room-co-ordinates.

The three-dimensional co-ordinates of a streak in the room is obtained from the two-dimensional co-ordinates on the two images of the streaks. Using the particle displacement ($\Delta X, \Delta Y, \Delta Z$) and the time-period Δt, the velocities can be evaluated.

In summary we can say that the length of the streaks are used to evaluate the velocities, the position and direction for the particles.

The velocities are in this method registered in the points in the room were the particles happen to be at the photograph-moment. From this result an interpolation can be done to get a vector-field over the whole photo.

RESULTS

Fig. 9 shows a visualisation of the jet with smoke and particles respectively.

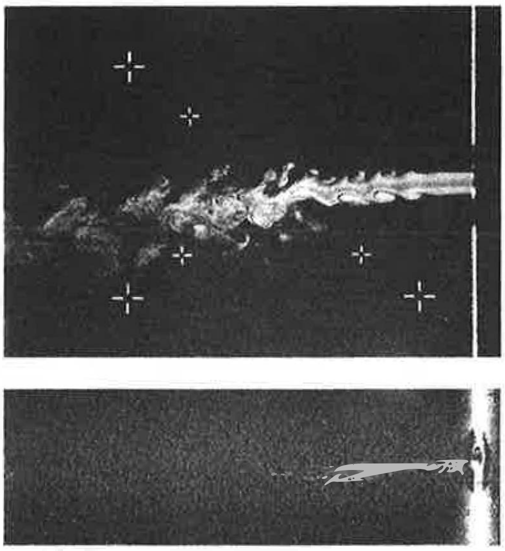

Fig. 9: Visualisation of jet flow
Above: Smoke
Below: Particles

Both the photo with particles and the one with smoke show that the jet has a tendency to go downwards.

By using the PSV method on a jet we have been able to measure the three-dimensional velocities. A number of streaks have been found and the velocities, position and direction for the particles has been calculated, see Fig. 10. The length of the arrows represents the velocity of each particle.

The limits for the light-sheet could be seen in Fig. 10. No particles should be found

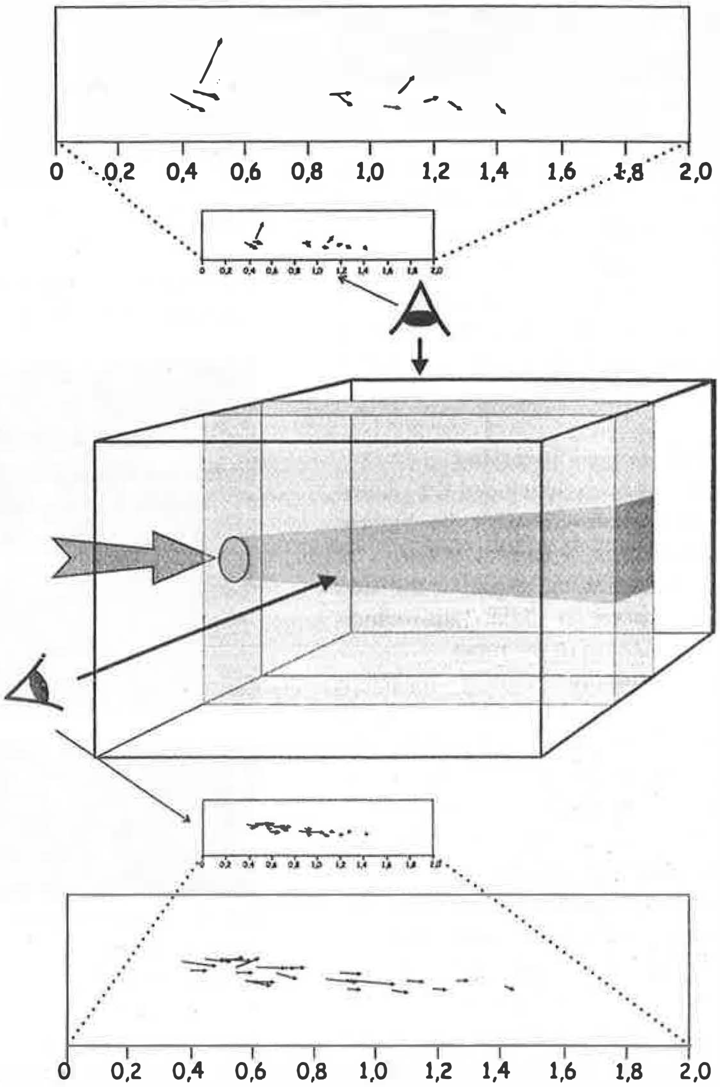

Fig. 10: Recorded particle velocities (The scale is in m)

outside these limits. Many particles had z-co-ordinates that were outside the lightsheet and must therefore be wrong. These particles are not included in the results.

In the comparisation with the results from the film probe the PSV-measurements are systematically lower.

The photo with smoke gives a good visualisation of the jet. It has also been possible to measure the length of the three main regions; laminar flow area, entrainment area with big eddies and the irregular, turbulent area. This analysis has been compared with the results from the film probe measurements, see Fig. 11. For details of the jet flow, see Todde et al (1998).

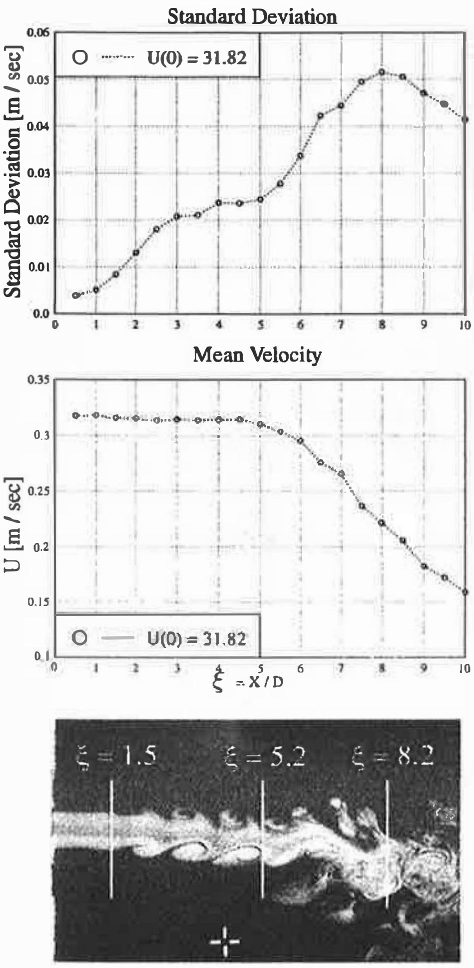

Fig. 11: Comparison of jet-regions

We can observe that the decay of the mean velocity starts just after the region of big regular eddies: ξ = 5.2. From the smoke picture the irregular turbulent region seems to start at ξ = 8.2. At the same distance the standard deviation attain its maximum value. Between region two and three, where the main eddies are destroyed, the standard deviation rises remarkably and attains its peak value.

DISCUSSION

The results show that this method can be a good tool for measuring three-dimensional velocities in rooms. This is one step closer to make the indoor-climate measurable, visible and understandable.

The main problem are the particles. Often the particles are coagulated in groups which makes them more easy to be seen but at the same time more heavy. Effort should be done to find proper particles.

Comparing the results with the film probe-measurements, showed that the PSV-method gives systematically lower velocities. This is probably due to a bias in the sense that the image processing program detects the particles with the highest light intensity. For the Image-processing program it is of course more easy to find the more intensive streaks. The particles with the highest light intensity are the largest ones which probably also have a smaller velocity.

Therefore particles with a uniform size distribution are required.

The difference in velocities and directions of the streaks looks a little strange. To understand this we must keep in mind that this is an instantaneous measurement of a flow field with high turbulence. A larger amount of streaks will improve the result.

The photographs evaluated in this project have a resolution of 3072*2048 pixels. Despite the fairly high resolution the thickness of the streaks are often just one or two pixels. This could be a reason for our errors in the out of plane co-ordinate (Z co-ordinate).

The remedy to this is a higher resolution. On the market today there are CAD-cameras provided with chips with 4096*4096 pixels resolution. This seem to be sufficient for our purposes. Access to CCD cameras with a high resolution would both give better results and a much easier work process.

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